Symposium on Optical Fiber Measurements (SOFM 2002), Sep 24-26, 2002, Boulder, CO, NIST Special Publication 988, pp. 45-48

High-resolution group delay measurements of a hydrogen cyanide gas cell using low-coherence interferometry

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Abstract: We demonstrate interferometric measurements of the relative group delay of a hydrogen cyanide gas cell with group-delay resolution of 0.3 ps at a wavelength resolution of 6 pm. We use simulations and measured data to illustrate the tradeoffs between group-delay resolution and wavelength resolution.

1. Introduction

Low-coherence interferometry is a fast and accurate method to measure the relative group delay (RGD) and spectral reflectance or transmittance of optical components. We have previously demonstrated repeatability better than 1 ps, and agreement with an independent measurement better than 1.5 ps [1].

In this paper we present high-resolution interferometric measurements of the RGD of a gas cell containing hydrogen cyanide ($H^{13}C^{14}N$) at a pressure of 13 kPa (100 Torr). Hydrogen cyanide has more than 50 strong absorption lines in the optical-communications C-band, making it very useful as a wavelength-reference artifact [2].

We chose to measure the relative group delay of a hydrogen cyanide cell for several reasons. First, the RGD of the cell can be predicted from a measurement of the cell's transmittance profile using the Kramers-Kronig relationship [3,4]. This predicted RGD is a valuable reference for estimating the uncertainty of our measurement. Also, the absorption lines of our hydrogen cyanide cell are very narrow (<100 pm), and therefore the group delay features are very narrow as well (<50 pm). The RGD of our hydrogen cyanide cell also includes weak hot-band lines, which are less than 2 ps deep. Therefore, an accurate measurement of the cell's RGD including the hot-band lines can be achieved only with a measurement system that has sub-picosecond RGD resolution and a wavelength resolution on the order of picometers. Thus, our hydrogen cyanide cell measurements will demonstrate the high-resolution capabilities of our interferometric measurement system. Additionally, the peak absorption wavelengths of the cell are well characterized; therefore, we can determine the absolute wavelength accuracy of our measurement system through a comparison with the NIST-certified absorption wavelengths of the cell. The final reason for measuring the cell's RGD is that the hydrogen cyanide cell might be applied in the future as an artifact for calibrating RGD measurement systems.

We have also created a simulation program to model the tradeoffs between wavelength resolution and RGD resolution. These tradeoffs are an important issue, regardless of the RGD measurement technique used, and wavelength and RGD resolution should always be specified together. Specifying an RGD resolution is meaningless unless the corresponding wavelength resolution of the measurement system is also specified.

2. Experiment

Our RGD measurement system is shown in Fig. 1. An erbium fiber superfluorescent source (BBS) provides our low-coherence signal. Our system consists of a fiber-optic Mach-Zehnder interferometer with the hydrogen cyanide cell (DUT) placed in one arm of the interferometer. We include a variable-length air path in the other arm of the interferometer, so that the total optical path difference (OPD) of the interferometer can be adjusted. At the output of the interferometer, two detectors (D1 and D2) receive two 1550 nm fringe signals that are 180º out of phase but have similar noise characteristics. By directing these two signals to a difference amplifier, we are able to reduce significantly the noise on our interference signal. We use a 1300 nm Nd:YAG laser (RL) to monitor the OPD as the translation stage moves. The interference signal created by the 1300 nm laser light is separated from the 1550 nm signal using a wavelength-division multiplexer, and the 1300 nm signal is sent to a zero-crossing detector circuit. This circuit triggers the A/D card sampling of the difference amplifier's output at every zero crossing of the 1300 nm interference signal. This gives a sampling rate of approximately 2.4 samples per 1550 nm fringe. This system is a significant improvement over our previous low-coherence interferometric system. The reference laser signal now travels in the same fiber as the broadband signal, virtually eliminating the large wavelength uncertainty that occurs when the two signals do not travel exactly the same path. Through improved electronics, we have also significantly increased the signal-to-noise ratio (SNR) of our system compared with our previous system (42.2 dB compared to 32 dB).

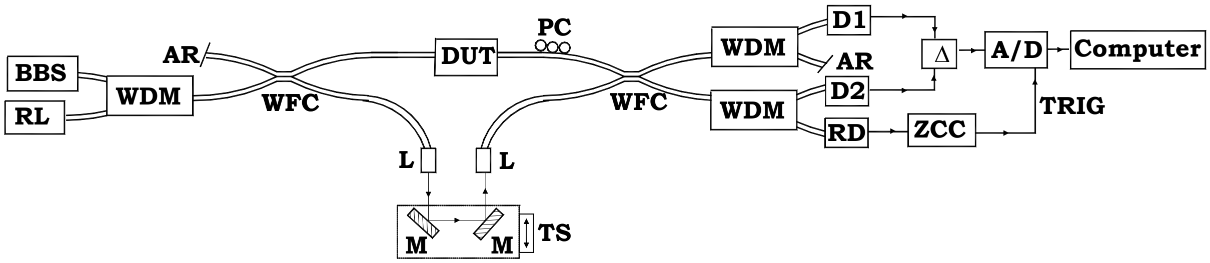

Figure 1. Diagram of the low-coherence interferometer used to measure the RGD of optical components. A/D: analog-to-digital board, AR: antireflection endface, BBS: broadband source, D1,D2: 1550 nm signal detectors, DUT: device under test, L: lens, M: mirror, PC: polarization controller, RD: detector for 1300 nm reference signal, RL: 1300 nm reference laser, TS: translation stage, WDM: 1300/1550 nm wavelength-division multiplexer, WFC: wavelength-flattened coupler, ZCC: zero-crossing detector circuit, Δ: difference amplifier.

To determine the RGD of our hydrogen cyanide cell, we first measure the 1550 nm interference signal as a function of OPD. We then calculate the Fourier transform of the interference signal, and separate the result into magnitude and phase. To calculate the RGD, we differentiate the phase of the Fourier transform with respect to wavenumber [1].

We determined the RGD of our hydrogen cyanide cell from the average of five independent measurements of the interferogram. Each measurement consists of 600,000 data points. The result is shown in Fig. 2, along with the RGD calculated directly from a measurement of the transmission of the gas cell using the Kramers-Kronig relations [4]. The standard deviation of the difference between our measured data and the Kramers-Kronig result is less than 0.3 ps, and the wavelength resolution is approximately 6 pm, as determined from the following formula:

$$\Delta\lambda = \frac{2\lambda_s^2}{N\lambda_r},$$

where $\Delta\lambda$ is the wavelength resolution, N is the total number of data points that are included in the interferogram, λ_r is the reference laser wavelength, and λ_s is the wavelength of the low-coherence signal. This formula is derived from the fact that the resolution of a discrete Fourier transform is inversely proportional to the product of the number of data points and the sampling interval [5].

3. Wavelength resolution and RGD resolution

We analyze the tradeoffs between wavelength and RGD resolution using a simulation program. Our simulation program starts from a measurement of the transmission of just one absorption line (P16) as a function of wavelength. Using the Kramers-Kronig relation, we calculate the complex refractive index of the gas cell [4]. Combining the complex refractive index with a measurement of our low-coherence source spectrum, we perform a Fourier transform to create a simulated interferogram. We add Gaussian random noise to the simulated interferogram to model the effects of noise in our experiment. The standard deviation of the Gaussian random noise was determined from the desired SNR. We quantize the result to simulate the discrete effects of our analog-to-digital (A/D) board, and truncate the interferogram to model the effects of interferogram length. We then calculate the group delay by taking a Fourier transform of our simulated, truncated interferogram and differentiating the phase. Comparing our simulation RGD results to the RGD predicted directly from the Kramers-Kronig calculation, we calculate the standard deviation of the difference between the two signals over a portion of the spectrum where the RGD is expected to be flat. The results are shown in Fig. 3, where the standard deviation between the two RGD results is shown as a function of wavelength resolution for three different values of SNR.

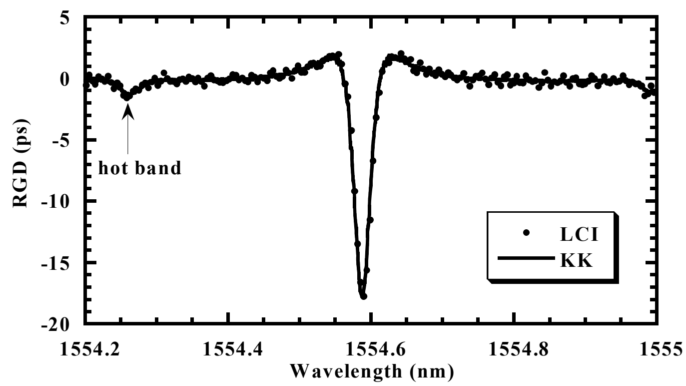

Figure 2. Plot of relative group-delay results as a function of wavelength. LCI=Low-coherence interferometric measurement results (average of five measurements); KK=Kramers-Kronig calculation.

In Fig. 3, we also show our results for the standard deviation between measured RGD data and the Kramers-Kronig RGD for several different SNRs. We varied our experimental SNR by adjusting the polarization controller shown in Fig. 1 to reduce the total fringe visibility. We could not directly determine the time-domain SNR of our measured data because the interference signal created by a narrow absorption line extends to very large OPD. Therefore, we determined the frequency-domain SNR of our measured data from a Fourier transform of the interferogram [6]. Using our simulations, we derived a linear relationship between time-domain SNR and frequency-domain SNR, and we used that linear relationship to convert the frequency-domain SNRs of our measured data to equivalent time-domain SNRs.

The wavelength resolution of our measurement is inversely proportional to the total length of the truncated interferogram. Thus, longer interferograms give finer wavelength resolution, but they also include more noise, and that noise degrades the group-delay resolution. The limiting factor is the experimental SNR; with higher SNR, both the wavelength resolution and RGD resolution can be improved.

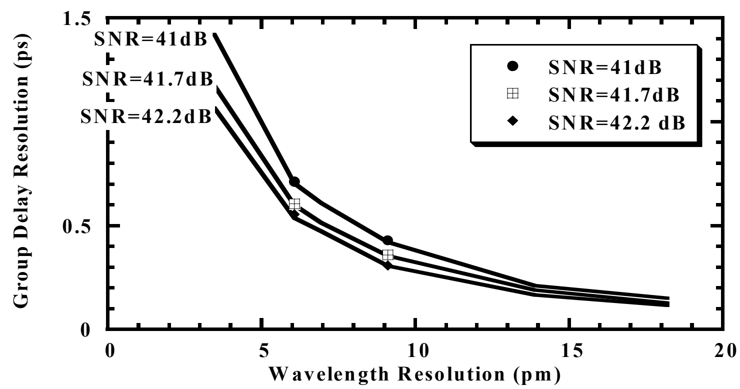

Figure 3. Plot of group delay resolution as a function of wavelength resolution for three different SNRs with no averaging. The solid lines are simulation results, and the data points are experimental results. Averaging multiple measurements will improve the group delay resolution by approximately $\sqrt{m}$, where m is the number of measurements.

4. Conclusions

We have demonstrated high-resolution interferometric measurements of the RGD of a hydrogen cyanide gas cell. When compared to a Kramers-Kronig prediction of RGD, our results have a 0.3 ps resolution at a wavelength resolution of 6 pm. We used simulations and measured data to illustrate the tradeoffs between group delay resolution and wavelength resolution.

Acknowledgements: The authors thank Tasshi Dennis of NIST for supplying the measured absorption data and Kramers-Kronig calculation routine.

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